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14. ABSTRACT Final Report for DURIP grant W911NF-14-1-0416 This DURIP grant has allowed for the purchase of three 3D printers: MCor Matrix, Stratasys Objet 260 Connex and Markforged Mark One. These printers (along with existing Stratasys Fortus 400mc) are an essential and invaluable part of the newly formed Aerospace 3D Digital Fabrication Laboratory at the William E. Boeing Department of Aeronautics & Astronautics at the University of Washington (UW) - Seattle. This departmental facility is					
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Report Title

Final Report: Advanced 3D printers for Cellular Solids

ABSTRACT

Final Report for DURIP grant W911NF-14-1-0416

This DURIP grant has allowed for the purchase of three 3D printers: MCor Matrix, Stratasys Objet 260 Connex and Markforged Mark One. These printers (along with existing Stratasys Fortus 400mc) are an essential and invaluable part of the newly formed Aerospace 3D Digital Fabrication Laboratory at the William E. Boeing Department of Aeronautics & Astronautics at the University of Washington (UW) – Seattle. This departmental facility is maintained by research engineers of the Aero/Astro department as well as by some of the researchers in the PIs lab (Composite Structures Laboratory; <https://www.aero.uw.edu/research/csl>). This facility is open to students and researchers in the Aero/Astro department at UW as well as to those in other departments at the University of Washington. The purchase of these printers to primarily design and print optimal cellular solids as cores of impact resistant structures will complement the research work carried out in the Composite Structures Laboratory at the University of Washington, and will guide research with respect to optimization of the microstructure of multi-material synthetic structures for mitigating high rate impact threats.

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

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<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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Names of Faculty Supported

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Sub Contractors (DD882)

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Final Report for DURIP grant W911NF-14-1-0416

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This DURIP grant has allowed for the purchase of three 3D printers: *MCor Matrix*, *Stratasys Objet 260 Connex* and *Markforged Mark One*. These printers (along with existing Stratasys Fortus 400mc) are an essential and invaluable part of the newly formed *Aerospace 3D Digital Fabrication Laboratory* at the William E. Boeing Department of Aeronautics & Astronautics at the University of Washington (UW) – Seattle. This departmental facility is maintained by research engineers of the Aero/Astro department as well as by some of the researchers in the PIs lab (*Composite Structures Laboratory*; <https://www.aa.washington.edu/research/csl>). This facility is open to students and researchers in the Aero/Astro department at UW as well as to those in other departments at the University of Washington. The purchase of these printers to primarily design and print optimal cellular solids as cores of impact resistant structures will complement the research work carried out in the Composite Structures Laboratory at the University of Washington, and will guide research with respect to optimization of the microstructure of multi-material synthetic structures for mitigating high rate impact threats. It is anticipated that such facility will attract interdisciplinary research with faculty from other departments on the University of Washington campus. The approximate life times of these printers are fifteen years. Capabilities of each of the printers are discussed below.



Figure 1: MCor Matrix 3D printer
(paper printer)



Figure 2: Stratasys Objet 260 Connex 3D printer
(graded polymer printer)



Figure 3: Markforged Mark One 3D printer
(composite material printer)

MCor Matrix (see Figure 1) produces high quality 3D printing and rapid prototyping in a fraction of the time taken by traditional 3D printers, using eco-friendly, inexpensive office paper and water-based adhesive. The build envelope is 256 mm x 169 mm x 150 mm. MCor produces the world's only paper based 3D printers using standard letter paper

to make 3D models for concept design evaluation, form-fit function testing, display and communication models, casting patterns and models for teaching. Models built on this printer can be tailored as a core material for lightweight sandwich structures. Another research goal is to be able to manufacture *multifunctional-layered structures*, by reinforcing nanoparticles in desired layers in the paper stack. We are currently exploring various methods that would allow impregnation of nanoparticles in papers, in order to build preliminary multifunctional structural models. This instrumentation is to be used in conjunction with an ongoing ARO sponsored effort on “Progressive damage and failure modeling of layered 3D textile composites.”

Objet 260 Connex (see Figure 2) allows building material models as large as 255 mm x 252 mm x 200 mm. It has high accuracy (16 micron per layer) and 14 photocopolymers to simulate a range of material properties. This printer will be useful in manufacturing thin walled shell structures (or its assemblage), which are used as energy absorbers. Specifically, we will be exploring the design of patterned cellular shell structures that have post-peak response that is more stable and that have higher energy absorbing capability compared to the usual thin cylindrical shell. In past studies (D’Mello et al. [1]), it has been shown that curved walls are better suited in their axial crumpling characteristics with respect to energy absorption compared against straight-sided axially crushed counterparts. Manufacturing of an assemblage of such shells will be guided by numerical models created in commercially available finite element software ABAQUS. The geometry will be imported to SolidWorks, which will export the geometry file as an STL file, which then can be used in printing the 3D model. Mechanical performance using compressive crushing of the 3D printed part will be studied in conjunction with the parent finite element geometry, which will be virtually compressed using the finite element method executed using the ABAQUS/Explicit solver. Moreover, the 3D printer will allow for printing non-uniform wall material in order to tailor not only wall thickness, but also wall material for the design of optimal energy absorbers. Lastly, such patterned shell structures can then be filled with softer elastomers, either manually through a secondary manufacturing process or within the 3D printer itself as a unified “*composite*” *cellular solid*. Introduction of such soft elastomers in the voids of such cellular solids will also allow for additional tailorability of their post-peak response. Preliminary results using uniform cellular, filled honeycombs are provided in D’Mello & Waas [2].

Markforged Mark One (see Figure 3) is a composite materials printer that can print carbon fiber, fiberglass, Kevlar and nylon. The build size is 320 mm x 132 mm x 154 mm with layer resolution of 0.1 mm. It can print solids that are 20 times stiffer and 5 times stronger than traditional ABS plastic models. Scaled models of various composite layups can be created using this printer. Such scaled models are effective in both research and in teaching. This printer will also allow students in the Aero/Astro department to manufacture lightweight composite parts for building drones and other model aircraft structures. Potential research directions that will be pursued by the PI are in the design of lightweight models for prosthetics, and also in manufacture of tailored face sheet material for sandwich structures (whose cores will be manufactured either by the MCor Matrix or by the Objet Connex).

References:

1. R. J. D'Mello, S. Guntupalli, L. R. Hansen and A. M. Waas, "Dynamic axial crush response of circular honeycombs," Proceedings of the Royal Society A, Vol. 468, pp. 2981-3005, 2012.
2. R. J. D'Mello and A. M. Waas, "Synergistic energy absorption in the axial crush response of filled circular honeycombs," Composite Structures, Vol. 94, Issue 5, pp. 1669-1676, 2012.